Atmospheric Environment Vol. 24A, No. 4, pp. 723–734, 1990.
Printed in Great Britain.

0004–6981/90 $3.00+0.00

STRUCTURE OF THE INDIAN SOUTHWESTERLY PRE-MONSOON AND MONSOON BOUNDARY LAYERS: OBSERVATIONS AND NUMERICAL SIMULATION

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(*First received* 15 *February* 1988 *and in final form* 2 *November* 1988)

Abstract—Characteristics of pre-monsoon and monsoon boundary layer structure and turbulence were studied in New Delhi and Bangalore, India during the summer of 1987. Micrometeorological towers were installed and instrumented at these locations to provide mean and turbulent surface layer measurements, while information on the vertical structure of the atmosphere was obtained using miniradiosondes. Thermal structures of the pre-monsoon and monsoon boundary layers were quite distinct. The daytime, pre-monsoon boundary layer observed over New Delhi was much deeper than that of the monsoon boundary layer observed over Bangalore and at times was characterized by multiple inversions. Surface, turbulent sensible heat fluxes at both sites were approximately the same (235 and 200 $W m^{-2}$ for New Delhi and Bangalore, respectively). Diurnal variations in the monsoon boundary layer at Bangalore were more regular compared to those under pre-monsoon conditions at New Delhi. One-dimensional numerical simulations of the pre-monsoon boundary layer using a turbulent energy closure scheme show good agreement with observations.

Key word index: Boundary layer, monsoon, turbulence.

1. INTRODUCTION

During the pre-onset phase of the Indian SW monsoon, a heat trough establishes over the Gangetic valley with strong, dry convection in the Planetary Boundary Layer (PBL). Advance of the monsoon over this region causes a transition from dry to moist convection which appears first in the eastern region of the trough. With the movement of a monsoon disturbance, this moist region generally migrates west with mesoscale organization of deep cloud clusters.

To study planetary boundary layer structure during pre-SW and SW monsoon conditions, field experiments were jointly conducted in New Delhi and Bangalore, India by the Indian Institute of Technology (IIT), New Delhi, the Indian Institute of Science (I.I.Sc.), Bangalore and North Carolina State University, Raleigh. Micrometeorological towers were installed and instrumented at these locations for the above study (see Fig. 1). The first phase of the field

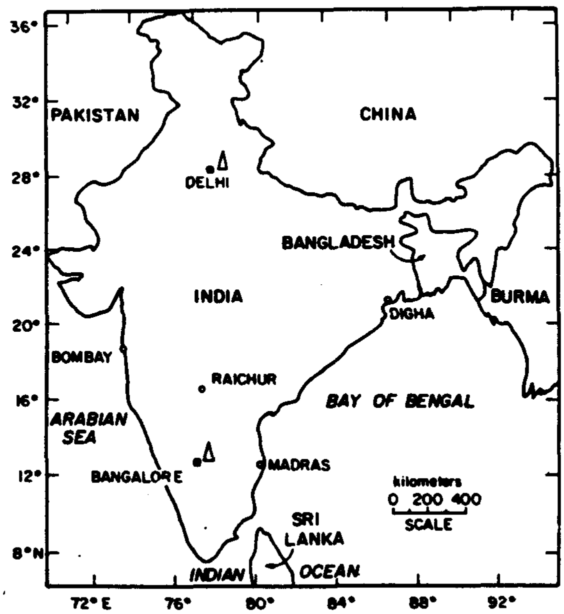

Fig. 1. Map of India showing the locations of New Delhi and Bangalore, the field sites used during the 1987 Indian Southwest Monsoon Experiment. Triangles symbolize the existence of micrometeorological towers at these sites.

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program occurred in New Delhi, where the main objective was to study the mean structure and turbulence of the tropical, convective boundary layer during pre-monsoon conditions. The second phase took place in Bangalore, about 1800 km south of New Delhi where the purpose was to study the structure and turbulence of the monsoon boundary layer. An additional objective of the field experiments was to study dispersion from an elevated source in the tropical environment; details of this study are presented by Templeman *et al.* (1988). Data obtained from New Delhi were later employed to test the effectiveness of a one-dimensional model in simulating the structure of the pre-monsoon boundary layer.

2. EXPERIMENT DESIGN

In New Delhi (28.43°N; 77.18°E), observations of the pre-monsoon boundary layer were made in mid-June. A permanent, 20 m open tower was constructed

Fig. 2. Micrometeorological tower installed in New Delhi. Instruments were mounted at the 2.1, 5.1, 10.4, 15.2 and 20 m levels.

on the IIT campus and instrumented at five levels with cup anemometers (2.1, 5.1, 10.4, 15.2 and 20 m) and at three levels with air temperature and relative humidity sensors (2.1, 10.4 and 20 m), as can be seen in Fig. 2. Wind direction measurements were made using a vane assembly at 20 m. Soil temperature was monitored at three levels, with the deepest sensor located at a depth of 0.8 m. Slow response wind instruments had a distance constant of about 1 m and the slow response temperature sensors a time constant about 10 s.

A fast response, vertical component sonic anemometer and a three-dimensional propeller anemometer were installed at a height of 15.2 m to provide turbulence data. Sonic anemometer had a distance constant of about 20 cm and the propellor anemometer about 60 cm. The sonic anemometer was also equipped with a fine wire thermocouple with a time constant of about 0.05 s. Temperature fluctuations obtained from this sensor were used along with the sonic anemometer vertical velocity fluctuations to produce an accurate measure of sensible heat flux by the eddy correlation method. These fast response instruments and a humidity probe located at 15.2 m were operated for an 8 day period at the beginning of the experiment. Humidity probe had a time constant of about 1 s. Slow response instruments were operated for a total of 5 weeks, with 3 min averages recorded through the first week of collection and 15 min averages thereafter. A photograph showing the configuration of the fast response instruments is provided in Fig. 3.

In Bangalore (13.03°N; 77.39°E), monsoon conditions generally prevailed and observations were made from the Indian Institute of Science campus during the first 2 weeks of July. Here an 18 m tower similar in design to the one in New Delhi was employed. Slow response air temperature, wind speed and relative humidity were measured at 1.25 and 18 m, supplemented by cup anemometers at 2.5 and 5.0 m. A wind vane was installed at 18 m to provide information on wind direction. The fast response anemometers and fine wire thermocouple used in Delhi were mounted at the 10 m level along with a fast response temperature sensor (platinum resistance type) and a slow response humidity sensor.

Two Campbell 21 × data loggers were used for recording observations. One data logger, assigned

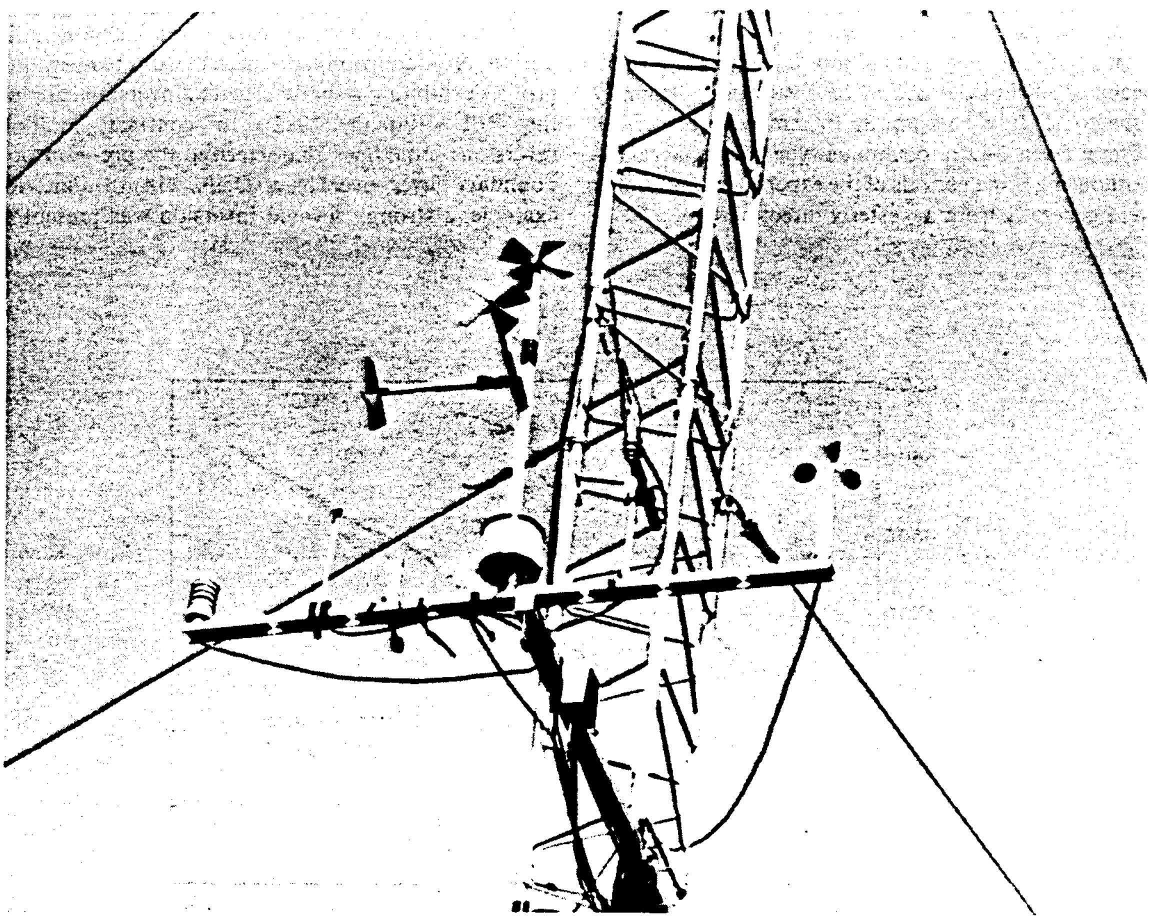

Fig. 3. Boom arrangement of the fast and slow response instruments at the 15 m tower level in New Delhi. From left to right are: a shielded slow response air temperature sensor; a mount for a fast response temperature sensor (not in use); a relative humidity probe; a Gill three-dimensional propeller anemometer; a sonic vertical velocity and air temperature fluctuation assembly; and a cup anemometer.

primarily to the fast response instruments, was programmed to calculate hourly averages, standard deviations and covariances. The majority of slow response instruments were connected to the other data logger which was programmed to calculate 3 min averages and standard deviations. Processed data were stored on magnetic tapes for later analysis and periods of unprocessed data were recorded daily under varying atmospheric stabilities. Information on the vertical, mean structure of the atmosphere to a height of about 5 km was obtained using miniradiosondes. Additional profile data were supplied by the Indian Meteorological Department in New Delhi.

3. THE 1987 INDIAN SOUTHWEST MONSOON

The 1987 monsoon was weak throughout most of India, causing one of the country's worst droughts. Although onset of the southwesterly monsoon over India was normal, it weakened by mid-June and did not advance to New Delhi during the experiment, which ended on 21 July. In fact, in New Delhi the monsoon set an 80 year record for the latest time of arrival. Thus, the planetary boundary layer experiments at New Delhi were typically of pre-monsoon type. General monsoon conditions were present in Bangalore, but only a small amount of precipitation occurred during the period of observation (from 29 June to 15 July only about 10 mm were recorded). Several levels of stratocumulus-type clouds were evident during some periods of the experiment and winds were generally from a westerly direction.

4. DATA ANALYSIS AND DISCUSSION OF RESULTS

4.1. *Structure of the planetary boundary layer*

Thermal structures of the pre-monsoon boundary layer at New Delhi and of the monsoon boundary layer at Bangalore were quite distinct, as can be seen from Fig. 4. This figure shows typical profiles of the daytime, virtual potential temperatures observed during the experiment. Height of the monsoon boundary layer at Bangalore was about 900 m during daytime convective conditions which were characterized by a superadiabatic lapse rate near the surface, a well-mixed layer and a sharply defined elevated inversion. The height of the boundary layer over the Arabian Sea was observed to be about 900 m with similar features during MONEX 79 (Holt and SethuRaman, 1985; Holt and Raman, 1986a) and about 500 m over the Bay of Bengal (Holt and Raman, 1987a). It is interesting to note that the basic thermal structure over Bangalore, about 200 km from the Arabian Sea coast (see Fig. 1), remains essentially the same in spite of the diurnal variation in surface heat fluxes over land. The pre-monsoon, daytime boundary layer at New Delhi was observed to be deeper, with heights of about 2500 m. Maximum height of the PBL generally varied between 2500 and 3000 m. Boundary layer heights near 2800 m have been observed over Raichur, India during NE monsoon conditions, with temperature profiles exhibiting a sharp, elevated inversion capping the PBL (Raman, 1982). In contrast, multiple inversions sometimes characterized the pre-monsoon boundary layer over New Delhi. On 18 June, for example, a strong, elevated inversion was present at

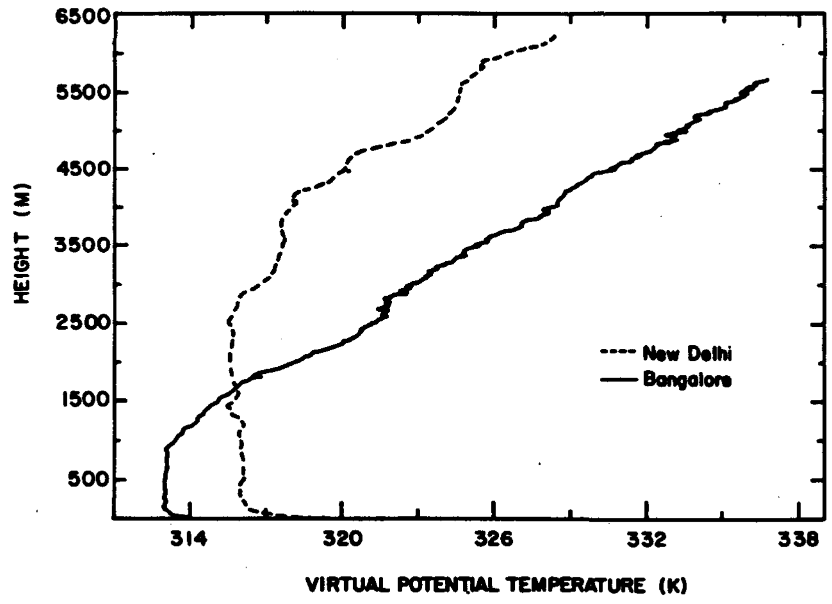

Fig. 4. Virtual potential temperature profile for 23 June (1528 LST) at New Delhi and 29 June (1432 LST) at Bangalore.

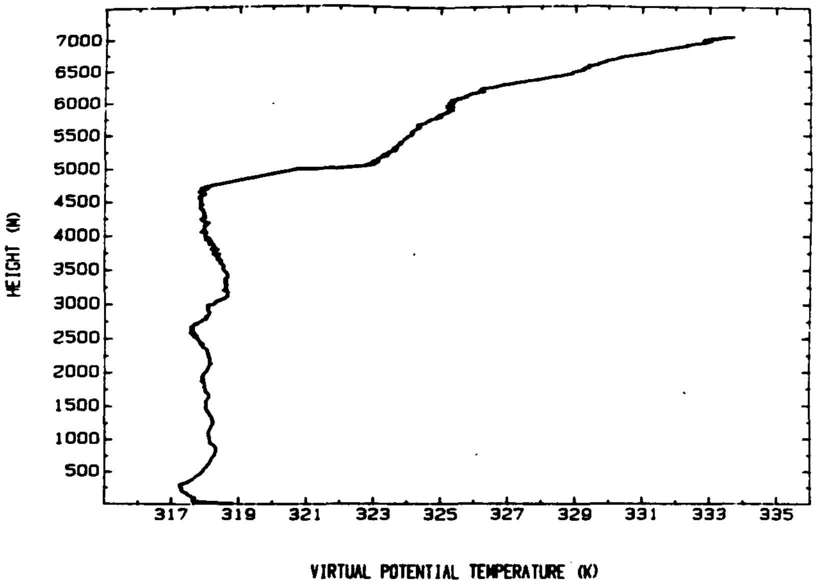

Fig. 5. Virtual potential temperature profile for 18 June at New Delhi. Sounding was initiated at 1517 LST.

4700 m, with a substantially weaker inversion at 2500 m (Fig. 5). PBL depth was thus estimated to be 4700 m. This height is approximately equal to that of the depth of the monsoon circulation (Fein and Stephens, 1987).

Specific humidities near the surface were generally higher at Bangalore (about 15 $g\,kg^{-1}$ of air) as compared to New Delhi (about 11 $g\,kg^{-1}$ of air). Profiles of specific humidity showed a gradual decrease with height over Bangalore, but a more uniform distribution over New Delhi. Relative humidity (r.h.) profiles over Bangalore exhibit an increase to the top of the boundary layer, with surface values near 60%. Values of r.h. above the boundary layer are fairly uniform (approximately 90% in one sounding, as shown in Fig. 6) and quite variable, indicating the occurrence of upper level advection of monsoon flow. Over New Delhi relative humidity also appeared to increase with height in the boundary layer, with surface values generally ranging from 18 to 50% (see Fig. 7) and upper level values approaching 90% in some cases. Values of r.h. were typically lower at New Delhi than those over Bangalore at all levels.

Surface, turbulent sensible heat fluxes were ob-

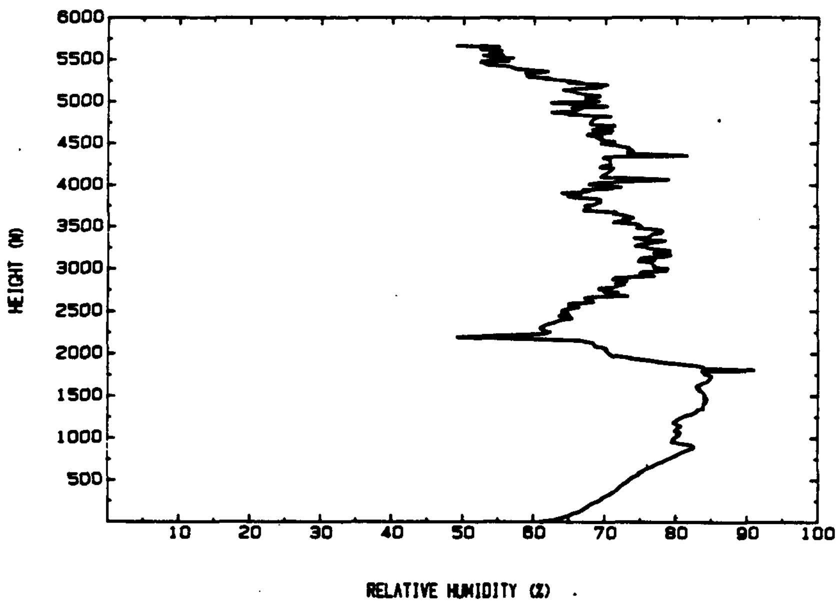

Fig. 6. Relative humidity profile for 29 June at Bangalore. Sounding was initiated at 1432 LST.

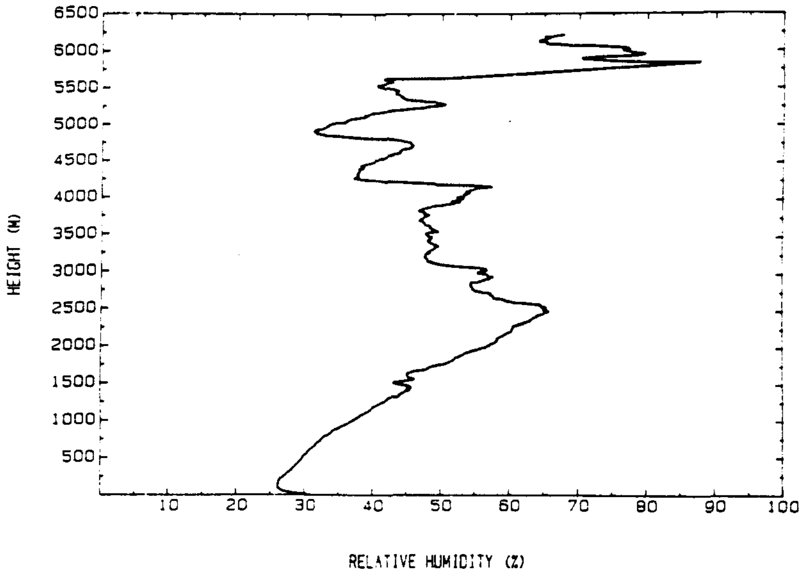

Fig. 7. Relative humidity profile for 23 June at New Delhi. Sounding was initiated at 1528 LST.

tained by the eddy correlation technique:

$$H_0 = \rho C_p (\overline{w'T'})_0 \quad (1)$$

where ρ is atmospheric density, C_p is specific heat at constant pressure, w' is the turbulent fluctuation of vertical velocity (measured by the sonic anemometer), T' is the turbulent fluctuation of temperature (measured by the fine wire thermocouple incorporated with the sonic) and the overbar denotes the average condition over the sampling interval. Daytime maximum values averaged about 200 $W m^{-2}$ at Bangalore and about 235 $W m^{-2}$ at New Delhi (see Figs 8 and 9). Near surface (2 m), maximum air temperatures were about 39°C at New Delhi and 27°C at Bangalore. During the experiment peak upward heat fluxes were observed to be about 300 and 275 $W m^{-2}$ at New Delhi and Bangalore, respectively. These values are almost an order of magnitude greater than the values between 15 and 30 $W m^{-2}$ obtained by Rao (1986) using surface and upper air mean observations over India. Sensible heat fluxes over the Arabian Sea and the Bay of Bengal during the Indian southwesterly monsoon are generally small, but the latent heat fluxes are relatively large, with values of the order of 300 $W m^{-2}$ (Holt and Raman, 1987b).

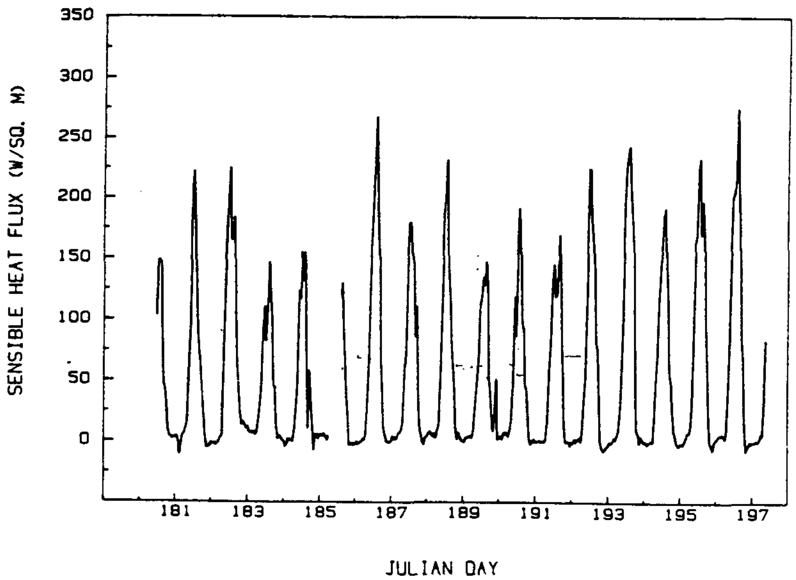

Fig. 8. Variation of surface turbulent sensible heat flux with time during the experiment in Bangalore.

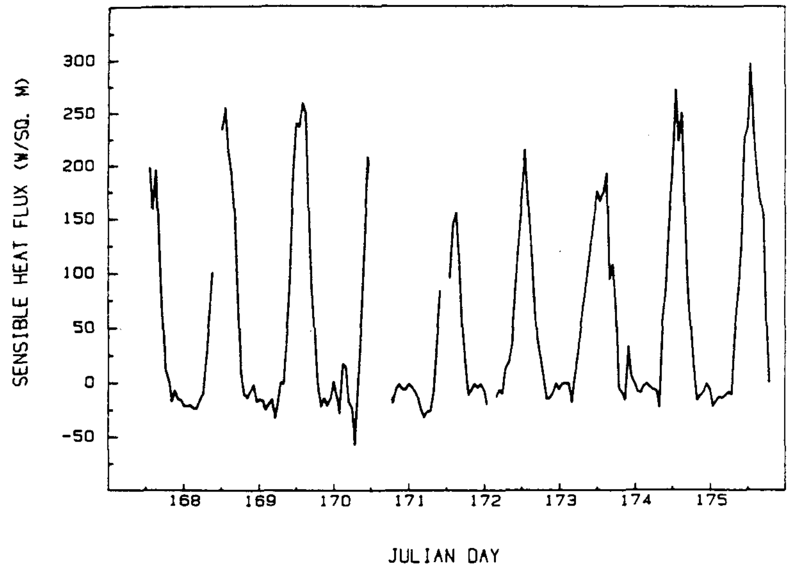

Fig. 9. Variation of surface turbulent sensible heat flux with time during the experiment in New Delhi.

Convective velocities, given by the equation:

$$w_* = \left[h \frac{g}{T} (\overline{w'T'})_0 \right]^{1/3} \tag{2}$$

vere 2.8 $m\,s^{-1}$ at New Delhi and 2.0 $m\,s^{-1}$ at Ban-;alore, as calculated from average maximum day time 'alues of $\overline{w'T'}$; average maximum daytime tempera-ures (T) and values of the respective boundary layer ıeights (h). Here g is the acceleration due to gravity. ˜he values obtained are characteristic of strong con-ection and significant vertical motion. For example, a value of 2.8 $m\,s^{-1}$ was observed over the Gulf Stream, off the eastern U.S., during an intensive cold air outbreak (Huang and Raman, 1988). Convective velocities in the monsoon conditions at Bangalore are relatively less than those in pre-monsoon conditions, but still large enough to indicate strong convection. Diurnal variation of surface, turbulent momentum flux at Bangalore was quite regular, with a maximum value of about 0.5 $N\,m^{-2}$ during the daytime and 0.1 $N\,m^{-2}$ during the night. Time histories of momentum flux for both locations are shown in Figs 10 and 11. These values were also determined by the

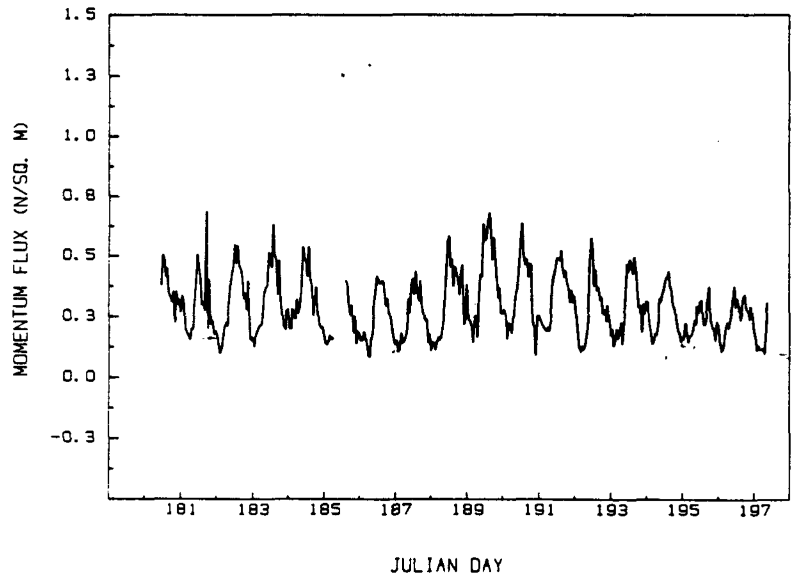

Fig. 10. Variation of surface turbulent momentum flux with time during the experiment in Bangalore.

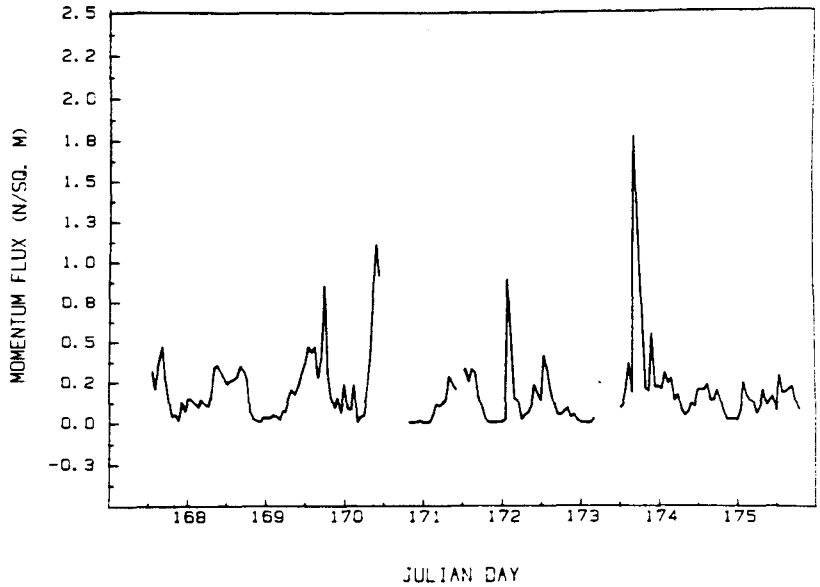

Fig. 11. Variation of surface turbulent momentum flux with time during the experiment in New Delhi.

eddy correlation method:

$$\tau = -\rho(\overline{U'w'})_0 \tag{3}$$

where $\overline{U'w'} = [(\overline{w'u'})^2 + (\overline{w'v'})^2]^{1/2}$ and u' and v' are the turbulent fluctuations of the horizontal velocity components. Maximum daytime values in New Delhi ranged from 0.24 to about 1.1 N m^{-2}, with night-time values of near zero. Average, maximum surface friction velocities (u_*) derived from turbulence covariance $\overline{u'w'}$ data were about 68 and 72 cm s^{-1} for New Delhi and Bangalore, respectively and occurred during daytime conditions when surface wind speeds were higher (values obtained for New Delhi were quite variable). The larger value of friction velocity at Bangalore is probably due to the higher wind speeds experienced there. Mean daytime winds at Bangalore were typically about 2.5 times higher than those at New Delhi.

Daytime peak values of the stability parameter z/L, where L is the Monin–Obukhov length, given by:

$$L = -T\frac{g}{k}\frac{u_*^3}{(\overline{w'T'})_0}$$

were observed to be about −2.1 and −1.4 for New Delhi and Bangalore, respectively (here k is the von Karman constant).

To determine roughness length (z_0), a stability corrected wind profile method was used. All hourly observations were used in conjunction with a log-linear profile relationship of the form (Wilczak and Phillips, 1986):

$$\bar{u} = \frac{u_*}{k}\left[\ln\frac{z}{z_0} - \Psi\left(\frac{z}{L}\right)\right]. \tag{4}$$

The function Ψ in stable air was estimated to be $-5(z/L)$ and in unstable air the following relation was used:

$$\Psi = \ln\left(1+\frac{x^2}{2}\right) + 2\ln\left(1+\frac{x}{2}\right) - 2\arctan(x) + \frac{\pi}{2}$$

where $x = (1-16z/L)^{0.25}$. Roughness lengths calculated using these equations were then averaged to yield the final estimates of 78 cm for the New Delhi site and 16 cm for the one in Bangalore.

4.2. *Dust devil of* 22 *June* 1987

During the period of observations in New Delhi an interesting yet relatively common meteorological event in the tropics occurred. Between 1600 and 1700 Local Standard Time (LST) a dust devil moved through the area of field operation, reducing visibility to less than half a kilometer. The hourly average wind speed at 15 m for 1700 LST was 8.2 m s^{-1}, with a wind direction of 240 degrees. Unprocessed data, averaged every 5 s for a period of approximately 28 min during the storm indicate a range of wind speed from 18 to 5 m s^{-1} at 15 m. The average momentum flux recorded for the hour ending at 1700 was 1.8 N m^{-2}, an increase of 60% over previously recorded peak values. Understandably, the average sensible heat flux shows a decrease for the hour in which the dust storm was most intense, in this case by nearly 50% compared to the average value for 1500 LST on this day.

The vertical, virtual potential temperature profile obtained from the sounding (not shown here) initiated at 1548 LST exhibits an interesting structure, with slightly stable conditions in the lower layers and unstable stratification in the upper layers of the PBL, up to a height of 3300 m, where an elevated inversion caps the whole layer. The negative potential temperature gradient aloft in the PBL is typical of the conditions conducive for the occurrence of dust devils.

Using the conditions of a homogeneous atmosphere, where the density is the same throughout the PBL, it can be shown that the lapse rate in such an atmosphere will be greater than the dry adiabatic lapse rate. With a value of about −3.4°C per 100 m, vertical overturning of air parcels normally takes place spontaneously, leading to dust devils (Byers, 1974).

5. NUMERICAL SIMULATION OF THE PRE-MONSOON BOUNDARY LAYER USING A ONE-DIMENSIONAL MODEL

Numerical simulations of the boundary layer were made using a one-dimensional, time-dependent barotropic planetary boundary layer model. The model consists of prognostic equations for east–west (U) and north–south (V) wind components and potential temperature (θ):

$$\frac{\partial U}{\partial t}-f(V-V_g)=\frac{\partial}{\partial z}\left(K_m\frac{\partial U}{\partial z}\right)$$
$$\frac{\partial V}{\partial t}+f(U-U_g)=\frac{\partial}{\partial z}\left(K_m\frac{\partial V}{\partial z}\right) \qquad (5)$$
$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial z}\left(K_h\frac{\partial \theta}{\partial z}\right)$$

where K_m and K_h are eddy viscosity coefficients of momentum and heat, respectively, and U_g and V_g are geostrophic wind components.

The model has 30 levels in the vertical (to a height of approximately 3 km) with logarithmic resolution. The numerical scheme is a simple centered-difference in space and forward in time. Surface layer profiles are assumed valid to the lowest computational level (about 45 m) where surface layer similarity is used. Above the surface layer, mixed layer theory based on Turbulent Kinetic Energy (TKE) closure is used. Evaluating simple first order and TKE closure schemes, Holt and Raman (1988) showed that parameterizations which include the variation of turbulent energy (E) and viscous dissipation (ε) give the best simulations of the mean and turbulent structure of the boundary layer. Thus, this E–ε parameterization scheme is incorporated into the 1-D model used for the simulation of the monsoon boundary layer. In this scheme, eddy viscosity coefficient K_m is determined from:

$$K_m=C_1\frac{E^2}{\varepsilon} \qquad (6)$$

and E and ε are calculated from additional prognostic equations (Duynkerke and Driedonks, 1987):

$$\frac{\partial E}{\partial t}=K_m\left[\left(\frac{\partial U}{\partial z}\right)^2+\left(\frac{\partial V}{\partial z}\right)^2\right]-\frac{g}{\theta}K_h\frac{\partial \theta}{\partial z}+C_2\frac{\partial}{\partial z}\left(K_m\frac{\partial E}{\partial z}\right)-\varepsilon \qquad (7)$$

where the first term on the right hand side (rhs) of (7) represents shear production, the second term buoyancy production, the third term turbulent transport and the fourth term dissipation; and

$$\frac{\partial \varepsilon}{\partial t}=C_3\frac{\varepsilon}{E}\left[K_m\left\{\left(\frac{\partial U}{\partial z}\right)^2+\left(\frac{\partial V}{\partial z}\right)^2\right\}-\frac{g}{\theta}K_h\frac{\partial \theta}{\partial z}\right]-C_4\frac{\varepsilon^2}{E}+C_5\frac{\partial}{\partial z}\left(K_m\frac{\partial \varepsilon}{\partial z}\right) \qquad (8)$$

where the first term on the rhs of (8) represents the generation of ε. For modeling purposes, the bracketed portion of this generation term is taken as MAX (shear, shear + buoyancy) (Duynkerke and Driedonks, 1987). The second term on the rhs represents destruction of ε and the third term represents the turbulent transport. Constants used in this parameterization for the 1-D model are taken as (Detering and Etling, 1985):

$$C_1=0.026 \quad C_2=1.35 \quad C_3=1.13$$
$$C_4=1.90 \quad C_5=0.77. \qquad (9)$$

The model was initialized at 0510 LST from the New Delhi mini-radiosonde sounding of 19 June. Geostrophic wind components were estimated from the 19 June surface pressure field. Integration for 15 h with a time step of 5 s requires approximately 10 CPU s on the CRAY XMP-24 with the TKE closure scheme. An important variable in the simulation of the monsoon boundary layer using the one-dimensional model is the diurnal variation of surface temperature. Based on observations, a sinusoidal variation of surface temperature with time is incorporated into the model. Surface temperature is a minimum of 30.8°C at 0510 LST and reaches a maximum of 44.0°C at 1500 LST.

Figure 12 shows the one-dimensional model simulation of potential temperature compared to observations from the 1217 LST New Delhi miniradiosonde sounding of 19 June. Also given is the 0510 LST initialization profile. Comparison of the initialization and 1217 LST profiles indicates substantial warming in the lowest 300 m. Surface heating plays an important role in the erosion of the strong surface-based inversion but advective effects cannot be ignored (Holt and Raman, 1985). The combined low level heat input from surface warming and advection serves to erode the strong surface-based inversion and by 1217 LST has substantially deepened the well-mixed layer (h) to roughly 1100 m. Remnants of the inversion though are still evident above roughly 300 m. It is in this region, the lowest 300 m of the boundary layer, that the model shows the largest deviation from observations (roughly 0.8°C). The model does well in predicting the growth of the boundary layer, estimating h as approximately 1000 m, and in predicting near surface temperature. However, the model is not able to effectively resolve the erosion of the surface-based inversion. Expansion to a two-dimensional model to include advective effects should improve prediction of the low level temperature structure.

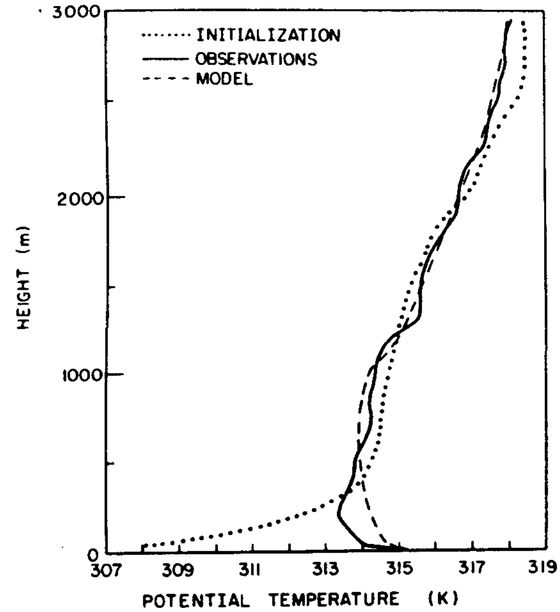

Fig. 12. Model simulations and observations of potential temperature for New Delhi on 19 June.

Figure 13 gives the variation of sensible heat flux for the period 18 June 0000 LST to 20 June 0000 LST at New Delhi. Unfortunately observations from tower data were not available for the period 1100–1900 LST on 19 June when the peak heat flux usually occurs. However, comparison of model results to flux profiles obtained on the days before (18 June) and after (20 June) in which monsoon conditions had not substantially changed indicate comparable values. The model predicts a maximum sensible heat flux of 192 $W m^{-2}$ at roughly 1400 LST on 19 June. For both 18 and 20 June, observed maximum fluxes of 270 and 165 $W m^{-2}$, respectively also occurred at roughly 1400 LST. Model simulations of negative heat flux in the early morning hours of 19 June (0500–0900 LST) show good agreement with observations. However, there is a time lag of one hour between the model results and the observations. Observations indicate a maximum negative heat flux of $-60\ W m^{-2}$ at roughly 0700 LST compared to $-60\ W m^{-2}$ at 0800 LST for the model. Heat flux is observed to become positive at 0800 LST compared to 0900 LST from model results.

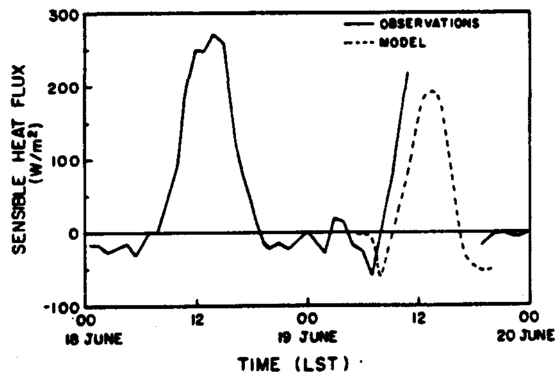

Fig. 13. Variation of sensible heat flux from 18–20 June at New Delhi.

Comparison of observations and model simulations of other parameters such as friction velocity u_* and convective velocity w_* was also made for 19 June. Model results show good agreement with observations. Both indicate maximum u_* values of approximately $0.90\ m s^{-1}$ at roughly 1500 LST (Fig. 14). Convective velocity w_* was approximately $1.62\ m s^{-1}$ at 1217 LST reaching a maximum of approximately $2.4\ m s^{-1}$ at 1400 LST as compared to $2.8\ m s^{-1}$ obtained from observations. Various stability and turbulence parameters predicted by the model are compared with the observations in Table 1.

Figure 15 shows the model simulation of the vertical profile of the TKE budget at 1400 LST on 19 June as calculated from Equation 7. In the lowest 300 m of the boundary layer, shear production and dissipation are the primary source and sink terms of TKE, respectively. Buoyancy production shows a near linear decrease with height and reaches a maximum negative

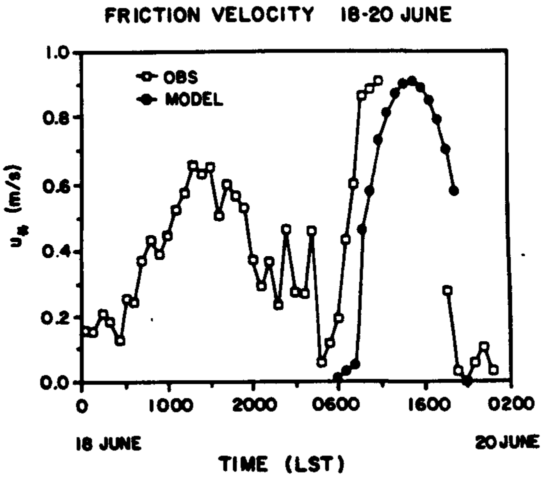

Fig. 14. Model simulations (closed squares) and observations (open squares) of friction velocity (u_*) for 18–20 June at New Delhi.

Table 1. Comparison of observations and model simulations 19 June 1987 1400 LST

Parameter	Model	Observations (typical)
h	2100 m	2500 m
w_*	$2.4\ m s^{-1}$	$2.8\ m s^{-1}$
u_*	$0.9\ m s^{-1}$	$0.88\ m s^{-1}$
$(\overline{w'\theta'})_0$	$0.159\ m s^{-1} K$	$0.195\ m s^{-1} K$
L	−366 m	−280 m
h/L	−5.7	−8.9

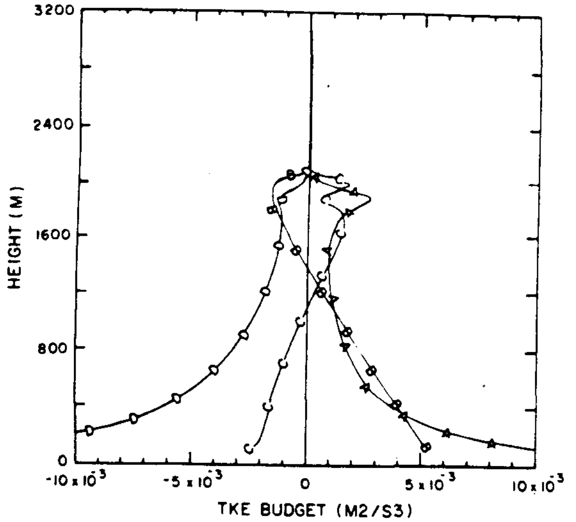

Fig. 15. Vertical profile of TKE budget as computed from the one-dimensional model at 1400 LST for New Delhi: shear production (A), buoyancy production (B), turbulent transport (C) and dissipation (D).

value near the inversion with roughly 27% of its surface value. Turbulent transport is a sink in the lowest half of the boundary layer, becoming a maximum source term near the inversion.

Comparison of the overland vertical profiles of TKE given for Delhi (Fig. 15) and over water profiles of the Arabian Sea (Holt and Raman, 1986b) indicates the importance of the underlying surface in generating turbulence. Shear production in the lowest 10% of the boundary layer over the more aerodynamically rough surface at New Delhi is generally much larger than that over the Arabian Sea. However, typical values of near-surface buoyancy production over the Arabian Sea are significantly larger than over land values, due to the contribution from latent heat. The vertical structure of dissipation and turbulent transport show no significant differences for New Delhi vs the Arabian Sea region.

6. CONCLUSIONS

Characteristics of pre-monsoon and monsoon boundary layer structure and turbulence were studied in New Delhi and Bangalore, India during the summer of 1987. The pre-monsoon boundary layer observed at New Delhi was much deeper (about 2700 m) compared to the monsoon boundary layer observed at Bangalore (about 900 m) and was at times characterized by multiple inversions. Surface momentum and sensible heat fluxes at New Delhi were higher, exhibiting free convection type of conditions. Relative humidity profiles at the two locations revealed increase in the PBL to values near 95 per cent at Bangalore (monsoon conditions) and much lower values of about 50 per cent at New Delhi (pre-monsoon conditions). Diurnal variations in the monsoon boundary layer at Bangalore were more regular as compared to those under pre-monsoon conditions at New Delhi. The thermodynamic structure of the PBL at Bangalore is essentially similar to the ones observed over the Arabian Sea during MONEX 79.

One-dimensional numerical simulations of the pre-monsoon boundary layer using a turbulent kinetic energy closure scheme show good agreement with observations from New Delhi tower data collected during June 1987. The model simulates well the growth of the convective boundary layer. However, the break-up of the strong surface-based inversion due to surface heating and advection is not adequately simulated by a simple 1-D model. Model results of the variation of sensible heat flux as well as of friction velocity (u_*) and convective velocity (w_*) agree well with observations.

Acknowledgements—This work was supported by the Division of International Programs, National Science Foundation under the Grant INT-82-19710.

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